PROJECT CHARIOT — PHASE III
PROGRESS REPORT

OGOTORUK CREEK BOTANICAL INVESTIGATIONS

PRELIMINARY STUDIES ON THE INFLUENCE OF FROST ACTION AND RELATED PHENOMENA ON THE VEGETATION OF THE OGOTORUK CREEK VALLEY

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This is a preliminary report and is

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One of the outstanding characteristics of arctic environments is habitat instability. Cold temperatures combine with soil moisture to cause intense freezing of the soil, and the soil responds by heaving, contorting, and otherwise moving both vertically and laterally to prevent the establishment of mature soils and vegetation that characterize more temperate regions of the world. Some of these processes are violent and so rapid that they exceed the reaction time of the plants growing in these environments. In such cases, all plant life may be destroyed for a time and growth will not be resumed until an amelioration of the environment occurs. The nature and intensity of these processes, collectively called frost action, are modified by the kinds of plants which are present, either directly by a physical restraint of the soil surface, or indirectly by preventing evaporation of water from soils and the retreat of permanently frozen ground, permafrost, to deep levels in the soil.

The tangible evidences that frost action is present are abundant almost everywhere in the arctic and are visible on the ground surface where they are referred to as frost features or patterned ground features. Included under these broad terms are such phenomena as polygons, nets, frost scars, and other peculiar surficial features.

The present study is primarily concerned with the interrelationships between frost action and the vegetation of the

Ogotoruk Creek Valley. Our previous reports (December 1959 Botanical Report and June 1960 Botanical Report) have referred to the presence of frost features in this area and their significance to the vegetation of the valley. I spent one month during the summer of 1960 in the Ogotoruk Valley conducting preliminary investigations on these problems. It quickly became obvious that frost action was most intense in the area of broad unconsolidated sediments on the lower slopes of the valley. Therefore, most of the available time was spent in those parts of the valley dominated by three of the vegetation types described previously, i.e., _Eriophorum_ tussock, _Eriophorum_-_Carex_ wet meadow, and _Carex_ _bigelowii_ frost scar types.* Some brief trips were made to other parts of the valley, and these are commented on briefly but the major part of this report will be concerned with interactions between frost features and vegetation patterns in the three vegetation types mentioned above.

The frost features will be described especially as they interfere with the normal expression of the vegetation within the study area. The history of each kind of feature will be outlined in terms of its production, maintenance, and degradation especially as revealed by the patterns of vegetation associated with it. Questions dealing primarily with the physical aspects of patterned ground formation will not be considered extensively here, because other research groups in Ogotoruk Valley are concerned with those parts of the study. It is hoped that collaboration between the soils investigators and the botanists may lead to an increased understanding of the interrelationships between the physical and the botanical processes.

I wish to acknowledge the helpful and illuminating discussions of the problems raised in the study with many colleagues at the Ogotoruk Base Camp, especially Mr. Herbert Melchior of the University of Alaska, Dr. N. Holowaychuk and Mr. James Petro of The Ohio State University, and Russell Campbell, George Moore, and Ruben Kachadoorian of the U.S. Geological Survey, Menlo Park, California.

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*For purposes of this report, the _Carex_ _bigelowii_ frost scar type retains its status as one of the vegetation types of the Ogotoruk Valley, but see December 1960 Botanical Report, page 43.

BACKGROUND

Patterned ground phenomena have attracted much attention, and a voluminous literature has accumulated on the subject. I shall not review it here, but Washburn (1956) and Cailleux and Taylor (1954) give comprehensive literature reviews and bibliographies. Also, Troll (1944) synthesized the information on patterned ground up to that time; his work stands as the classic paper in the general field. The purely descriptive and the physical aspects of patterned ground phenomena are most heavily represented in the literature. There are numerous unresolved controversies on classification of the features and especially on their origin. Washburn's paper is especially useful in obtaining a quick review of the latter.

Almost every botanical expedition to high latitudes (and in some cases high altitudes) has commented on the presence of patterned ground, and some of the best physical descriptions of frost features have been contributed by biologists; papers by Polunin (1934) and Raup (1947) are examples. Few papers, however, have demonstrated the interrelationships between the vegetation and the frost features. This is understandable because until recently there was little hybridization between the purely botanical fields on one hand and the geomorphological on the other. That increased understanding can come from such hybridization is strikingly demonstrated by a recent paper in this area by Hopkins and Sigafoos (1951).

The classification of patterned ground features used here follows Washburn (1956). His is a simple, comprehensive scheme which is easily applied in the field. It would be a mistake to think that his system is completely "natural," i.e., representing a genetic relationship between the features included in it. The origins of patterned ground are so poorly understood that the resemblance of two types of features may be completely superficial. The confusing synonomy predating Washburn's system is not reproduced here. Not all of his categories are mutually exclusive, as will be shown below.

The terms used in this paper are taken primarily from Bryan (1946), Hopkins and Sigafoos (1951), and Washburn (1956). They have been used extensively in the literature and seem to be rather generally accepted by both geologists and botanists.

Washburn's classification system has as its basic dichotomy "sorted" vs. "nonsorted features." Sorted features are those that occur in an initially heterogeneous substrate; under the influence of frost action the coarse materials are in some manner separated from the fines and become laterally displaced from them.* Should this action occur on level ground, the sorted features are approximately circular or polygonal in shape with coarse particles forming a border around the fines. As the slope increases, the influence of gravity also becomes important, and the features in some situations assume an orientation approximately parallel with the slope and in others a step-like arrangement at right angles to the slope. Ultimately, on steep slopes the fine materials are arranged in longitudinal stripes up and down the slopes, the stripes of fines being separated from each other by stripes of coarse materials. Thus, in sorted features one may recognize circles, polygons, nets, stripes, and steps.

The same features occur in fine-grained homogeneous substrates such as loess and marine lacustrine deposits and other unconsolidated materials, but in these cases they are produced through mechanisms which cause the earth to contract in a polygonal network or heave due to the segregation of masses of ice in the soil. Superficially both sorted and nonsorted features resemble each other because they have similar sizes and shapes; the mechanisms by which they are produced are, however, considerably different.

The classification system breaks down in some special cases.

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*It should be pointed out that sometimes sorting occurs only vertically, i.e., stones are brought to the surface and remain more or less in place. In such cases, it seems incorrect to say that the features are nonsorted, though many of the forms like this in the Ogotoruk Valley would be so categorized according to Washburn' system.

In fine-grained soils, for example, where some coarse particles are also present, the feature may appear to be nonsorted, but upon close examination is found to be sorted to some extent. In other words, the borderline between sorted and nonsorted features is obscure at times, and in such cases there may be an overlap of genetic processes.

In spite of these weaknesses, Washburn's system is useful especially for descriptive purposes where the investigator is primarily concerned with the surface manifestations of geomorphological processes.

Before proceeding with the observations in the Ogotoruk Valley, some generalizations and assumptions on the properties of patterned ground will be made; these will be useful in the discussions below.

1. On the frost susceptibility of soils, Taber (1930) pointed out that certain kinds of soils are more likely to be susceptible to frost action than others, especially silty and clayey soils which may hold more water (as ice) than is ordinarily present in the interstices between individual particles. In these soils, masses or lenses of clear ice may be present segregated from the soil itself, displacing it either laterally or vertically. The soil movement in these situations is commonly referred to as frost heaving or thrusting. This expansion may amount to as much as 45 per cent (Williams, 1956). Williams (1959: Figure 2) shows the upper grain-size composition for frost susceptibility in soils. Penner (1958) has pointed out that ice segregation depends not only on pore size, but also on permeability; thus, a silty soil which has larger pores than a heavy clay still shows more ice segregation and heaving because heavy clay is relatively impermeable to water movement. Data on mechanical analyses of Ogotoruk Creek soils are not yet available, but obviously some of them are frost susceptible.

2. Ice segregation in fine-grained soils is especially favored by slow freezing under conditions of a plentiful water supply. This is due to the fact that a nucleus of ice in the soil attracts water to it from surrounding unfrozen soils.

Water movement will occur through capillary or "suction" processes (Penner, 1958, p. 3) so long as the soil remains unfrozen.

3. Processes by which patterned ground is formed today occur at reduced intensity compared to some unspecified earlier time. Thus some features may be regarded as "fossil"-remnants of earlier activity.

4. The length of time required to produce mature frost features is unknown, as is the length of time during which individual features persist. Both are assumed to be highly variable for any type of feature.

5. Under the existing climatic regime, it is assumed that some years are optimum for producing frost features while others are less so.

6. Vegetation is related to frost features in that vegetation may prevent frost action in some cases and may help stabilize existing frost features in others through its insulation of the soil and the physical restraint of soil movement by roots.

7. For the purposes of this report, frost features are considered to be active only if the physical phenomena which produce or maintain them are such that recognizable changes in the nature of the vegetation associated with them occur. Completeness of plant cover, the growth of lichens on rocks, or the absence of any surficial features which suggest genesis of edaphic discontinuities are taken to be criteria of inactivity. Thus, long-term changes (e.g., a general regional climatic change) are not taken into account here, since the magnitude of the change is insufficient to be reflected in recognizable comparable shifts in the vegetation.

SOME GENERAL OBSERVATIONS ON THE RELATIONSHIPS BETWEEN THE VEGETATION TYPES

The classification of vegetation types currently in use at Ogotoruk Creek is based on both the plants and the physiographic characteristics associated with the vegetation. It should be explained that this is not standard phytosociological practice, but the categories were rather subjective at the beginning of the study and were thought to be convenient and easy to apply not only by the botanists but by the other scientists working in the valley. When the quantitative analyses have been completed, we may apply the standard nomenclatorial terminology of American synecology should this be thought desirable. On the basis of the quantitative examinations some splitting of our rather broad categories may be found to be necessary. In this report, however, the vegetation units will be those described in the December 1959 Botanical Report.

The primary vegetation types recognized in the valley are the following: *Dryas* fellfield, *Eriophorum* tussock, *Eriophorum-Carex* wet meadow, *Carex bigelowii* frost scar, *Eriophorum-Carex* solifluction slope, *Dryas* steps and stripes, ericaceous shrub polygon; and mixed grass-sedge saline meadow. Some other vegetation types occur, but as these show less homogeneity than the others, they have been considered, at least preliminarily, as a heterogeneous group of plant communities which can be lumped into some tentative categories, as snow-bed communities, gravel bar and bench communities, and talus slope and rock outcrop communities. Descriptions of the types and communities were included in the December 1959 Botanical Report.

Figure 1 shows a general scheme of the interrelationships between the vegetation types and their relationship to certain environmental gradients. I shall review this chart briefly here and comment more particularly on some of its details later.

On the exposed, windswept, upland areas bordering the broad Ogotoruk Valley floor a sparse vegetation is present, and it is characterized especially by the presence of *Dryas octopetala*.

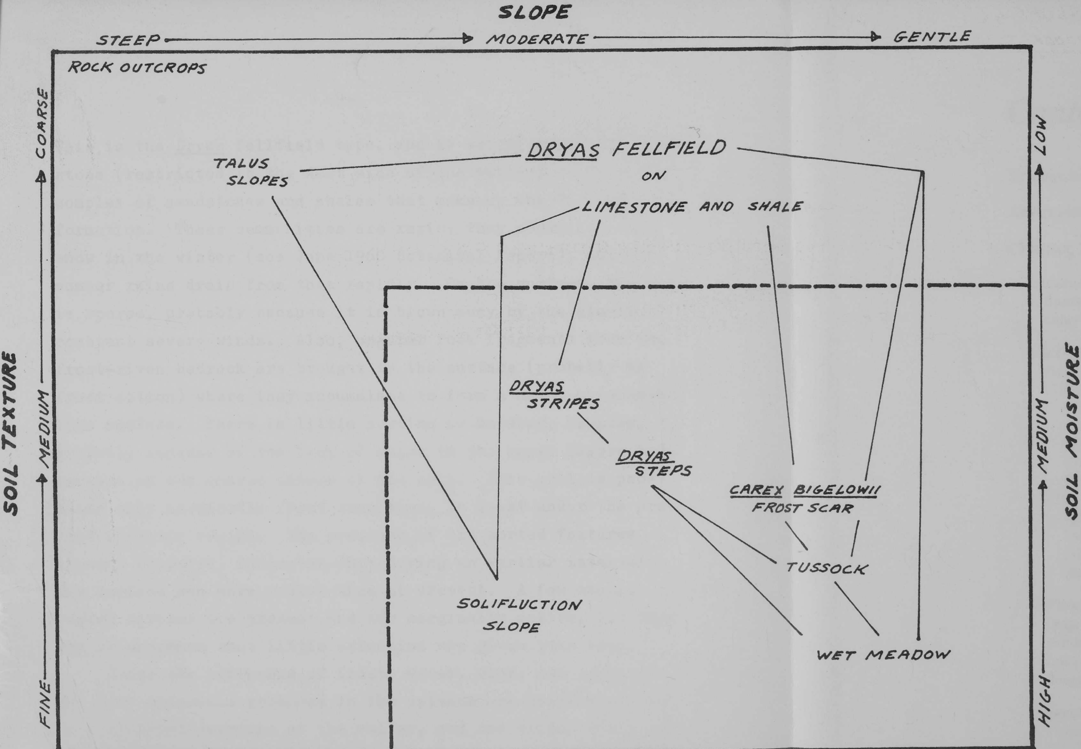

FIGURE 1. Relationships between slope, soil moisture, soil texture, and frost action in some vegetation types in the Ogotoruk Valley. Lines indicate recognized transitions between types. Area within dashed line is most subject to modern frost action, and contains numerous patterned ground features. Fossil features are found outside dashed line

This is the _Dryas_ fellfield type, and it occurs on either limestone (restricted to the west side of the valley) or on the complex of sandstones and shales that make up the Tiglikpuk formation. These communities are xeric; they accumulate little snow in the winter (see June 1960 Botanical Report), and the summer rains drain from them rapidly. On the surface, the soil is sparse, probably because it is blown away by the almost constant severe winds. Also, angular rock fragments from the frost-riven bedrock are brought to the surface (probably by frost action) where they accumulate to form a hard, pavement-like surface. There is little sorting or heaving, however, probably because of the lack of water in the upper layers and because of the coarse nature of the soil. This soil is probably only marginally frost sensitive, at least under the presnet climatic regime. The presence of old sorted features (fossil features) indicates that during an earlier interval the surface was more active than at present. A few small, sorted circles are present and are marginally active, but they are so uncommon that little attention was given this type.

Under the influence of frost, water, wind, and gravity, the fine materials produced in the uplands are carried to the less elevated portions of the valley, and the valley floor is covered with fairly deep deposits of unconsolidated materials. On the west side of the valley, there is one kind of transition between the _Dryas_ fellfield type and areas of deep unfrozen soils which support _Dryas_ steps and stripes and another between the _Eriophorum_-_Carex_ solifluction slope type. Both of these types occur on moderate slopes; the reasons for the differences in these two transitions seem to be related to moisture and perhaps to parent materials (see below). The _Dryas_ steps and stripes type occurs on dry localities which accumulate only moderate amounts of snow, while the solifluction slope type accumulates large amounts of snow in the winter, and even in late summer is wet underfoot. The increased moisture helps support dense vegetation, and permafrost is present only a short distance from the surface.

On the east side of the valley neither the Dryas step and stripe types nor the Eriophorum-Carex solifluction slope type appear to be present. The reasons for this are not clear, although there are several obvious differences between the two sides of the valley which, acting together, may account for it. There is limestone on the west side of the valley; more snow accumulates on the west side; and the west side is better insolated. It is interesting to note that the Dryas step and stripe communities seem to be associated with the limestone and they contain numerous species which require more warmth during the summer, e.g., the numerous legumes which occur there. And, as indicated above, the Eriophorum-Carex solifluction slope type occurs on slopes in areas of snow accumulation.

On the east side of the valley, the Dryas fellfield type usually is bordered rather sharply at lower altitudes on moderate to gentle slopes by the Carex bigelowii frost scar type, a type not found on the west side. It is assumed that this sharp boundary marks the upper limits of frost senstive soils because it usually coincides with a topographic discontinuity where fine materials carried down from the slopes accumulate. As will be shown below, this type is characterized by intense frost action. Considerably more water is present than in the Dryas fellfield type, and permafrost is present not far below the surface. The reasons for the absence of this type on the west side of the valley are not understood, but the difference in parent materials may be at least partially responsible. Probably more important, however, is greater frost action on the less well-insolated east side of the valley.

On the gentle valley floor, two main vegetation types occur. They are the Eriophorum tussock type and the Eriophorum-Carex wet meadow type. The following transitions from the slope types occur: (1) from fellfield to tussock or wet meadow; (2) from solifluction slope to wet meadow; (3) from Dryas steps and and stripes to tussock or wet meadow; and (4) from Carex bigelowii frost scar type to tussock. Tussocks occur on drier soils than wet meadow, and an obvious transition occurs between them. In some areas, the two types are so thoroughly mixed that it is difficult to separate them.

Both the Eriophorum tussock and Eriophorum-Carex wet meadow type extend to places where the flat valley surfaces are cut by incised drainages. In the drainage systems, various combinations of communities are found depending on several factors. If the drainage system is oriented at right angles to the prevailing wind so that snow accumulates (i.e., east-west), snow-bed communities of various types are found, often superimposed on or mixed with the willows which are characteristic of gravel bars and benches. The length of time during which the snow persists determines the composition of these snow-bed communities. If the drainage is oriented parallel to the prevailing wind, however, it will usually be covered with different kinds of willow communities, the nature of these depending on the age of the drainage. The zone of active meanders in Ogotoruk Creek, for example, supports one kind of willow community, while the only occasionally flooded bench immediately above this has a different kind of willow stand. Permafrost is not present near the surface under the active zone, while it is usually found within a few centimeters under the less active part. Frost features are not present under any of these conditions.

Some of the less important vegetation types and communities are omitted from the chart. One may expect to find saline meadow communities on flat ground often flooded by the sea. Ericaceous shrub polygon and Carex bigelowii high center polygons are omitted because the conditions necessary for their existence are not yet understood.

DESCRIPTION AND NOMENCLATURE OF OGOTORUK VALLEY PATTERNED GROUND FEATURES

The frost features occurring in the Ogotoruk Creek Valley are listed according to vegetation type in Table 1. Interpretation of activity of the features sometimes requires a subjective evaluation; for example, while no ice-wedge polygons are being newly formed in the Ogotoruk Creek Valley today, it is difficult to assess the activity of the ones now present. Conceivably, some of them are "growing," while others are probably static, while still others are being actively eroded by stream cutting. Large numbers of excavations would be required to settle this problem. However, inasmuch as the area lies within the area of continuous permafrost (see Péwé, 1957), there is reason to believe that the temperature conditions are such that ice-wedge growth by accretion is occurring under the present climate. In any event, the changes in the vegetation produced by ice-wedge growth must be slow -- too slow to be detected in short term studies of the kind being considered here. For these reasons, these types of features were not studied. For purposes of background, however, brief descriptions will be given in this section of features known to occur in the valley. Specific comments on the most active of these will be given in section on Vegetation-Frost Feature Relationships.

Nonsorted Features

Frost Scars

The general term "frost scar" will be used to describe nonsorted circles in any of the vegetation types in the valley. A more specialized terminology has been used in some other studies, and these names will be indicated where considered important. In general, frost scars consist of circles or ovals of bare mineral soil surrounded by the vegetation of the type in which they occur (Figure 2). They are variable in size, and in addition to the common shapes indicated, they may be highly irregular.

Table 1. Vegetation types and frost features in the Ogotoruk Creek Area.

Vegetation Type	Patterned Ground Feature	Activity
Dryas fellfield: limestone	Sorted polygons, nets (large) Sorted circles, polygons (small)	Inactive Activity weak
Dryas fellfield: shale	Sorted circles, polygons (small)	Activity weak
Eriophorum tussock	Unsorted polygons (ice-wedge type) Unsorted circles Mudflows*	Active (?) Active Active
Eriophorum-Carex wet meadow	Unsorted polygons (ice-wedge type) Unsorted circles	Active (?) Active
Carex bigelowii frost scar	Unsorted circles	Active
Solifluction slope	Solifluction terraces*	Active
Dryas steps and stripes	Unsorted steps and stripes	Active
Ericaceous polygons	Unsorted polygons (ice-wedge type)	Inactive (?)
Carex bigelowii high-center polygons	Unsorted polygons (ice-wedge type)	Inactive (?)
Mixed grass-sedge saline meadow	None	
Snow-bed communities	None	
Gravel bar and bench communities	None	
Miscellaneous: 1. Talus slopes 2. Citellus mound 3. Aquatic 4. Strand	Sorted stripes None None None	Inactive

*Related to frost action, but not patterned ground features sensu Washburn (1956).

Figure 2. A typical frost scar in wet meadow vegetation showing sparse vegetation, convex surface, and mineral soil. Note remains of dead plants on surface and border trench sharply outlining scar. Ogotoruk Valley near Plot 1, 17 June 1960.

An "average" sized scar is one to three meters in diameter; some are smaller, while some irregular ones are many meters in length and from one-half to one meter in width. In some vegetation types they are abundant, while in other parts of the same type or in different types they may be scarce. The centers of the scars are often domed convexly, or they may be flat or even somewhat depressed. Permafrost is invariably present beneath them, being deepest in the center of the scar and shallowest at its margins. If the scar is convex on the surface, one can always find lenses of clear ice in the soil under the scar.

Many ideas have been proposed to explain the origin of scars, but there have been no definitive studies on this problem. There seems to be general agreement, however, that a scar forms by the unequal accumulation of ice under a flat surface, with the subsequent heaving and rupturing of the surface in those areas which accumulate most ice. The reason for the disparity in ice accumulation is not understood, but it has been suggested that initial breaks or differences in thickness in a vegetation mat set up temperature differentials in the soil, with the result that the least well-insulated soils freeze first in the fall and subsequently accumulate water to the ice nucleus. The ice grows by accretion with the resulting scar production. Some of the requirements for this hypothesis have been tested under laboratory conditions (see Penner, 1958) and have been found to be correct, but field studies are lacking. Other explanations also have been proposed.

The relative age and activity offrost scars can probably be estimated by their size, shape, and the degree to which they have been colonized by vegetation. Youthful scars are almost always devoid of vegetation, and sometimes show fragments of dead or dying vegetation on their surface. The size of the scar is probably the least reliable indicator of its age. I do not completely agree with the idealized diagram of Hopkins and Sigafoos (1951:82-83) showing the evolution of a frost scar (peat ring in which a gradual increase in size with time is indicated.

In many instances in the Ogotoruk Valley, it appears that the frost scar attains its upper size limits in the first season of its existence. In fact, in my experience the smallest scars are often the oldest ones -- being the remnants of once greater size and activity. Older frost scars are often partly or completely covered by vegetation.

A frost scar occurring in a more or less homogeneous vegetation is microenvironmentally distinct from the surrounding area. It is probably always drier or wetter than the vegetation-covered soil around it, and is warmer in the summer and colder in the winter. Convex scars are more exposed to the wind which accelerates the drying process and renders them liable for wind erosion. Thus, the vegetation occupying a scar is often distinct from that of the surrounding area, and the species which grow there are dependent on the activity and other physical characteristics of the scar, as well as the kinds of the species which surround it.

Polygons and Nets

While the frost scars, discussed above, are rarely arranged in a regular pattern other more conspicuous features show such striking regularity, especially from the air, that they have remarked upon by scientists and non-scientists alike. To this class of phenomena belong the large so-called ice-wedge polygons and nets (Elton, 1927). As suggested by Washburn (1956), these forms probably always occur in nets and never singly, a point which has been seized upon to explain their origin. The size of these structures in the Ogotoruk Valley (10 to 30 meters in diameter) compares with that of similar structures described from great areas of the north. Though commonly referred to as polygonal nets, the individual "meshes" may be almost square, the joints of the net being at right angles to each other. Indeed, Lachenbruch (1959) suggests that the idealized pattern should be like this. The fine-grained centers of the network are separated from each other by a depression in some cases (Plot Numbers 4, 23, 42, and 46) or by a ridge in others (Plot Numbers 34, 37, and 48).

Of the many hypotheses proposed for the origin of ice-wedge polygons, those having to do with contraction of the soil under the influence of drying, and low temperature ice contraction seem to have gained the greatest acceptance (Washburn, op. cit., p. 848-849). According to Britton (1957) a cyclic process occurs in the formation and eventual partial degradation of ice-wedge polygons on the Arctic Coastal Plain near Point Barrow, Alaska. In the Ogotoruk Creek Valley, however, such a cycle has not been noted.

As in other areas (Washburn, op. cit., p. 832), small non-sorted structures (frost scars) occur in the central areas of the large ice-wedge polygons.

The December 1959 Botanical Report also refers to two other types of nonsorted (ice-wedge ?) polygons in the Ogotoruk Valley. These are the so-called high center polygons (Plots 17 and 49) and the ericaceous polygons of Plots 40 and 50. The high center polygons are about the same size as those occurring in the *Eriophorum* tussock areas and probably represent tussock areas which have become better drained in time. Their position on small interfluvial ridges supports this idea. The ericaceous polygons are smaller, three to six meters across, and occur in the deeply weathered colluvium on the lower slopes of the west side of the valley. Both are thought to be inactive, and in some areas they are being actively eroded by gulley-cutting.

Steps and Stripes

Nonsorted steps and stripes are mostly restricted to the deeply weathered limestone soils on the west side of the Ogotoruk Valley. These are somewhat similar to the vegetation stripes and turf-banked terraces of Sigafoos (1951) and Antevs (1932). Washburn (1956) discusses both of these patterned ground features.

The steps and stripes in the Ogotoruk Valley are obviously related to each other. They occur on the same kinds of substrate under similar exposure, and the plants associated with them are often the same. The primary difference between them is that the steps are arranged across the slope and the stripes parallel to it, stripes occurring on steeper slopes than the steps. It seems likely, in fact, that the differences in pattern are related to slope angle.

The pattern formed by the steps and stripes is emphasized by alternating bands of bare soil and vegetation, the vegetation in this case being predominantly Dryas octopetala with other species scattered throughout its mats.

The recognition of this distinct but fairly limited pattern resulted in our classifying it as one of the vegetation types in our December 1959 Botanical Report. Inasmuch as nonsorted steps and stripes must be discussed exclusively in terms of the Dryas step and stripe vegetation type, I shall defer further discussion of their characteristics to that part of this report (page 46).

Solifluction Terraces

Another phenomenon widespread in arctic areas, but not discussed by Washburn (1956), is that of solifluction terraces. They are not, strictly speaking, patterned ground phenomena, but because they often occur in areas where patterned ground is present and apparently under the influence of processes associated with frost action, they are frequently included in studies of frost features. As with other frost features, a large literature has accumulated. In a series of recent papers by Williams (1956, 1957a, 1957b, 1959), most of the important literature is cited; thus, I shall not repeat it here. Some of the synonyms of solifluction terraces are solifluction lobes and tongues, soil lobes, lobate terraces, etc.

Solifluction terraces are essentially lobate masses of soil which occur on gentle to moderate slopes and which support vegetation on their upper and frontal surfaces. They often have steep frontal banks measuring one meter or more in height, the size of the bank usually increasing with the slope angle. The upper surfaces of the terraces are often flattened somewhat so that the angle formed by the upper surface of the terrace and the horizontal is usually less than the angle of the slope with the horizontal. Behind the frontal bank, the terrace may be distinguishable from 5 to 15 meters upslope. Smaller terraces occur in some environments (Williams 1957a). The most common terraces observed in the Ogotoruk Valley belong to the large type, and as has been demonstrated in other studies, their presence depends on an abundant water supply, moderate to steep slopes, the presence of frost sensitive soils, freezing-thawing processes, and, perhaps, permafrost. In the Ogotoruk Valley, the terraces are limited almost exclusively to the west side of the valley where these requirements are better fulfilled. As mentioned earlier, soil development is more pronounced on the calcareous soils of Crowbill Ridge, and long-lasting snow-beds in those areas assure a fairly constant water supply, at least during the early to mid-summer period.

Williams (1957a:51) states that "the commonest theory for the cause of solifluction is that the soil is reduced to a plastic consistency by the excess water, from both melting ice and snow, in the soil at thaw." In such cases, it has been further suggested by many workers that the soil will "flow" downhill under the influence of gravity and aided considerably by the presence of an impermeable layer such as bedrock or permafrost. Williams demonstrates, however, that terrace formation occurs on sites which do not meet these criteria (e.g., absence of permafrost or bedrock close to the surface), and suggests other possiblities such as frost-heave "creep" and the reduction of shear strength in soils which have been disturbed by ice layer formation. Moreover, he has carefully analyzed some of these factors in the field and has prepared mathematical models which are helpful in explaining the observed phenomena. He stresses the importance of examining each case of solifluction on its own merits and cautions against generalizing cause-effect relationships at this stage in our knowledge.

The solifluction terraces in the Ogotoruk Valley are probably active, i.e., they are moving slowly downhill. This statement is based on the fact that humus layers extend upslope under the terraces, and these layers are more or less continuous with the vegetatioh directly in front of the frontal bank. The detection of movement in solifluction terraces requires elaborate instrumentation, but studies on terraces elsewhere indicate that movement is usually in terms of a few millimeters annually. Other studies (e.g., Williams 1957b) have also shown that there is often a zonation of vegetation on the terraces. Unfortunately, time did not permit further study of these features in the Ogotoruk Valley.

Sorted Features

Sorted Polygons, Circles, Nets

Sorted polygons of two general types occur in the Ogotoruk watershed. The first of these is undoubtedly "fossil" in nature and is found only on the limestone ridge on the west side of the valley. In this type, the rock borders consist of blocky or angular limestone fragments up to four or five decimeters in diameter, and they surround fine-grained centers which are up to three meters in diameter. Inasmuch as this kind of frost feature is inactive, no special attention was given to it other than to note and map the location of the features. Their presence in the area is interpreted as an indication of once more rigorous climate of unknown time and duration. Similar features are thought to develop in periglacial climates such as are present today in northern Greenland and elsewhere. Periglacial climates are ordinarily considered to be both colder and wetter than non-periglacial climates, a reasonable supposition in light of the direct evidence available in areas where these climates occur today. It should be mentioned that frost features also occur in cold, dry climates (e.g., Péwé, 1959).

The second type of sorted polygon is also unusual in the Ogotoruk Valley, though not nearly so rare as the large stone polygons mentioned above. These small polygons or circles occur in substrates which consist of some fine-grained residual soils and in addition rock fragments of coarse gravel size or slightly coarser. In such substrates and under comparatively weak frost action, small sorted circles, polygons, and, rarely, nets are found. These have fine-grained centers up to one meter in diameter with the small stones arranged in characteristic patterns at the margins. Under the present climate these small features are probably active only in the most favorable years, i.e., years when moisture levels are high during the freezing-thawing periods in the spring and fall. Their fine-grained surfaces usually support at least some plant growth, an almost certain sign of their weak activity. It is informative to note that these features are mostly limited to the tops or gently sloping sides of the Dryas ridges. They are better developed in the limestone than in the shale, probably because of the somewhat deeper soils found there. In many places they are completely absent or barely evident. It is suggested that with somewhat more moisture, the activity of these small forms would increase. I have seen small sorted structures of this type in several alpine areas in the Rocky Mountains, and in those environments it is possible to find intense frost action associated with increased amounts of moisture. That severe wind erosion reduces the amount of both snow and soil present on the ridges has been demonstrated, and this, in part, helps to expalin the paucity of patterned ground features in these places.

Sorted Steps and Stripes

Sorted steps and stripes are mostly absent in the Ogotoruk Valley, though there are a few "fossil" stripes on the upper parts of Crowbill Ridge.

VEGETATION-FROST FEATURE RELATIONSHIPS

Eriophorum-Carex Wet Meadow Type

Frost scars are the only active features in the *Eriophorum-Carex* wet meadow vegetation type. Their size and shape conforms to the general description given above (see Figure 3). Widely separate areas in the valley were visited during the summer of 1960 and there seem to be no differences between the frost scars along the coast and five to ten miles inland. In the wettest parts of the type, and there are few scars. Here, the surface of the vegetation mat is constantly wet, and even in late summer water stands a few centimeters deep over the bases of the sedges. Such areas are found in the vicinity of the lakes in the upper valley, on some of the low terraces bordering Ogotoruk Creek, or in some cases on very wet moderate slopes such as around Plot 39.

As the soils become drier, frost scar abundance increases, and under situations which might be considered median for growth of the sedge species, there may be as many as 30 to 40 scars per acre, these in various stages of development. As the soil moisture levels become less favorable for the growth of *Carex aquatilis* and *Eriophorum angustifolium*, the numbers of scars increase still further, but here the situation is complicated by the transition to the *Eriophorum* tussock type. I shall discuss the special problems of the transitions separately below and for the moment will concentrate on those parts of the type which are clearly wet meadow.

The frost scars of this type are apparently the same as the peat rings of Hopkins and Sigafoos (1951), though their category is somewhat broader and includes some forms which are probably not present in the Ogotoruk Valley. According to Hopkins and Sigafoos (*op. cit.*, 82-83), the peat ring grows centrifugally through several years and expands both vertically and horizontally, i.e., a convex doming of the soil of the ring occurs as the ring grows radially. This kind of sequence may occur, but in the Ogotoruk Valley it has not been clearly recognized. If a frost scar starts its developement as a small patch of soil, perhaps five to ten centimeters in diameter, and grows annually until it reaches a size of one to two meters, one should expect to find a size gradient from small scars to the largest of them. I was not able to locate such a sequence, and my observations of hundreds of individual scars in the Eriophorum-Carex wet meadow type seem to indicate that a scar reaches its maximum size in the first year or two of its appearance. It is possible, of course, that a considerable amount of subsurface activity takes place before the scar actually breaks the surface and destroys the vegetative mat, but I was unable to see any surface evidence of such preliminary stages.

There is other evidence which favors the quick-formation hypothesis of scar genesis. On some obviously active scars, the remains of E. angustifolium and Carex aquatilis plants were found over the entire surface of the scar. In several instances, these plants were of the previous year's growing season, though it was not clear whether they had been heaved out of the soil in the previous fall or the current spring.

The marginal peat ridges found by Hopkins and Sigafoos (1951) on the Seward Peninsula were lacking in the Ogotoruk Valley, at least in structures which could definitely be called frost scars. Instead the scars in the wet meadow type are bordered by a small trench completely surrounding the scar (Figure 2). The trench is lower than the surrounding unbroken vegetation mat, and often contains standing water. It should be mentioned here that peat-ringed frost scars remarkably similar in size and appearance to the scar shown by Hopkins and Sigafoos (ibid., p. 78) were found in the Upper Slate Creek Valley, but in this case, it appears that the scars result from the feeding activities of animals -- caribou in winter, and ground squirrel in summer. Caribou were known to be present at various periods during the winter of 1959-1960, and their tendency to dig circular feeding craters by pawing through the snow is well known. H. Melchior (in litt) attributes some of their characteristics to the feeding activities of ground squirrels. It is not suggested that the peat rings seen on the Seward Peninsula have a similar origin, but it does point to the necessity of careful interpretation of phenomena which are least superficially similar.

Permafrost is invariably present in the *Eriophorum-Carex* wet meadow type. Under the unbroken sedge sod it is very close to the surface, usually within 20 cms., while under the open scar it is deeper, the depth probably depending on the size and age of the scar and the degree to which it has been recolonized by vegetation. For example, under bare, apparently active scars in areas near Plot 1, on 2 July 1960 the permafrost depth varied from 25 to 47 cms., while under the adjacent vegetation mat it was shallower and less variable, averaging about 17 cms., but varying only from 15 to 20 cms. in depth. These measurements are not strictly comparable, however, because the surface convexity of the scar often adds 10 to 20 cms. to the reading. Ice lenses are present and abundant under a convex scar; this accounts for the upward displacement of the soil.

An active frost scar is partially or completely devoid of vegetation, but once its surface no longer undergoes vertical movements engendered by frost action, it is a suitable substratum for the growth of plants. The plants that then grow there are recruited from those species in the valley that find the habitat satisfactory for growth and which also have the ability to migrate to these areas. Not all frost scars are alike in the environmental combinations they present to the plants. For example, some scars are elevated only slightly above the surrounding ground, while the tops of others may be 20 cms. or more above the sedge mat. The low scars are wet, and the higher ones considerably drier, especially in the upper four or five cms. Furthermore, it appears that in some cases the frost scars become depressed in time and after a few years are barely recognizable from their surroundings (Figure 3).

Figure 3. An old frost scar in wet meadow vegetation barely discernible from its surroundings. Ogotoruk Valley near Plot 1, 2 July 1960.

Figure 4. An old frost scar in wet meadow vegetation. Note shrubs of *Salix pulchra* on scar surface. Ogotoruk Valley, 2 July 1960.

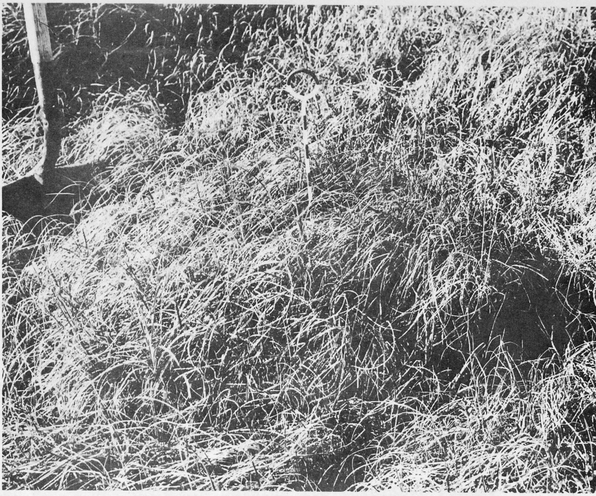

Figure 3 (above) Figure 4 (below)

But in the scars which are elevated, the plants are different from the almost pure Eriophorum-Carex sod. A sequence such as the one presented below probably occurs.

Almost all of the frost scar surfaces fall within the amplitude of Eriophorum angustifolium, and this species quickly invades even semi-stabilized surfaces. Sometimes renewed activity of the scar eliminates it before much growth has occurred. It seems probable, however, that complete E. angustifolium cover coincides with the recession of activity of the scar surface, and that plant growth even helps stabilize the surface by reducing the amplitude of the heat flux of bare soils. Other plants of drier habitats invade the scars. Hierochloe alpina, Potentilla emarginata, Salix pulchra, Androsace chamaejasme, and Caltha palustris are all pioneers on wet meadow frost scars, the last species only on the wettest scars. Carex aquatilis may also grow on the wetter frost scar surfaces, but the more elevated scars are probably outside its tolerance range. On old scars, Eriophorum has often formed a tight mat, and it, together with Salix pulchra and Betula nana, may grow to the exclusion of almost all other species (Figure 4).

Scars which have been recolonized to this extent probably persist for a long time, and old, somewhat elongate ridges occurring in some areas of wet meadow may owe their origin to repeated frost scar formation and stabilization in elongate patterns running at right angles to the slope. Such elongate patterns of active frost scars have been recognized in other parts of the valley as will be shown below. These ridges, of course, may be unrelated to frost scar production. Peat formation occurs on the tops of old stabilized frost scars, and after a sufficiently long, but unknown, time the mounds of fresh mineral soil that characterize young and mature frost scars are no longer visible.

It must be emphasized that not all frost scars are stabilized in their elevated condition. If this were true, one should expect to find that the numbers of hummocks increased annually, and over a relatively short period of time the character of the tundra surface would change radically from a flat, wet meadow to a higher, drier undulating surface which would support much different kinds of plants. Frost scars, however, after remaining active for a number of years, for reasons not understood, subside back to the level of the tundra surface again. Thus, a cyclic pattern of events is indicated. The length of time that frost scars remain elevated above the tundra surface depends on the success of colonization of the scar by plants; the height to which heaving occurred; soil moisture levels in the scar; ice lens melting or persistence; compaction of the soil; wind erosion; and probably many other variables. The fairly simple botanical cycle is thus underlain by a complex set of physical processes which are difficult to analyze.

Another question of interest that remains unanswered is the future of an area that has undergone frost heaving. It is possible that such an area is more susceptible to future frost heaving than areas which have never been disturbed. In fact, N. Holowaychuk (viva voce) has suggested this on the basis of preliminary soil observations. As an alternate suggestion, I offer the idea that once a frost scar has formed on a tundra soil, that particular spot may be "immune" from future disruptions for a number of years, or until the peculiar series of events that initially produced the scar are duplicated. If, as Penner (1958) suggests, frost heaving in soils is related to pore size and pore size distribution, it seems likely that frost heaving changes these properties somewhat. This may result in a reduction in frost susceptibility for a time. These problems fall outside the botanical investigations, but one cannot avoid speculating on some of them when studying these interesting phenomena.

Other cyclical processes will be suggested below. As far as I know, cyclic processes in the arctic tundra frost scars have not been described previously, though Billings and Mooney (1959) describe a similar series of events in small sorted polygons in the alpine tundra of the Medicine Bow Mountains of southern Wyoming.

Eriophorum Tussock Type

Frost scars also occur in the Eriophorum tussock vegetation type, and the general characteristics of the scars apply here (Figure 5). The numbers of frost scars per unit area vary considerably according to the moisture and other conditions of the site. In the wettest areas, i. e., those sites which are transitional to wet meadow, there are large numbers of scars; in areas optimum for tussock growth, the number of scars decreases rapidly but they become more numerous as dry sites are approached. In fact, on some of the upland tussock sites, the frost scar pattern often becomes a sinuous interconnected complex where it is difficult if not impossible to separate one scar from another (see Figure 19, p.). The area between Plot 30 and the airstrip is typical of the wet situation described above; optimum tussock growth occurs in areas like Plots 4 and 36, while Plot 54 is a good example of habitats on the dry end of the range. The number of frost scars per acre poses interesting problems which shall be discussed later.

Since tussocks are intimately associated with frost scars, it will be useful for the following discussions to discuss their interesting botanical characteristics.

Tussocks are in essence clones of the species producing them, and at maturity they consist of more or less circular masses of tightly interwoven plants which stand above the substrate; each tussock is separated from adjacent tussocks by a channel of varying width, depending mostly on the vigor of the tussocks on the site. The tussocks we are dealing with here belong to Eriophorum vaginatum (= E. spissum of some authors), one of the cotton-grasses; tussocks are produced by other genera and species elsewhere, e. g., Carex lugens forms tussocks in many parts of Alaska.

Tussock formation begins with the germination of individual seeds of the species on moist, mineral soils. The primary growth of the tussock is followed by a tendency for the production of large numbers of lateral basal shoots resulting in a rapid increase in the diameter of the tussock. Just how rapidly a tussock enlarges is a badly needed statistic for reasons which will be pointed out below. In an effort to solve the problem, I dissected several

Figure 5. A typical frost scar in the tussock type. Note convex surface, small tuft of dead Deschampsia caespitosa on right center of scar, and shrubs of Salix pulchra invading scar from margins. Ogotoruk Valley, 13 July 1960.

tussocks of different sizes and worked out an aging method which is successful on small tussocks but probably of little value on large ones. The method is based on the observation that each living shoot of the tussock produces annually an "average" number of leaves, and though the upper portions of the leaves die and fall from the plant, their bases are exceedingly resistant and remain embedded in the mass of the tussock more or less intact for several years. By comparing the number of leaves produced by the oldest living shoots during the current growing season with the number of old leaf bases remaining on the plant, one may achieve some estimate of the age of the tussock. The method is also based on the admittedly shaky assumption that a living shoot produces the same number of leaves annually during each year of its existence. While this is probably true for the first few years of tussock growth, it is almost certainly not true as the tussock approaches its maximum size. In any event, the results for small tussocks seemed to fit a pattern of growth which seems fairly consistent when plotting diameter against age. The results are presented in Figure 6. In tussocks older than six years, no reliable data were obtained, but the rate of growth of young tussocks is indicative of a rapid growth rate in general, and it gives rise to the speculation that "full-sized" tussocks need be no older than 10 to 20 years.

Tussock size does not increase indefinitely, though the maximum size varies from site to site. For example, under the conditions prevailing in Plot, 4, tussock size (for randomly selected tussocks) averaged 25 cms. in height and about 27 cms. in diameter; while in Plot 54, which seems marginal for tussock growth, the average height was only 15 cms. with diameters averaging 19.4 cms. The density of tussocks per unit area is also highly variable as indicated above. In Plot 4, there are about 5 tussocks per square meter, while in Plot 54 there are only 2.5 tussocks per square meter. Situations intermediate between the two described here were observed elsewhere in the valley. It is interesting to note that the largest tussocks do not occur in the areas where they are most dense. Some of the largest tussocks in the valley were found in the broad, flat area between Chariot base camp and Slate Creek. Individual tussocks

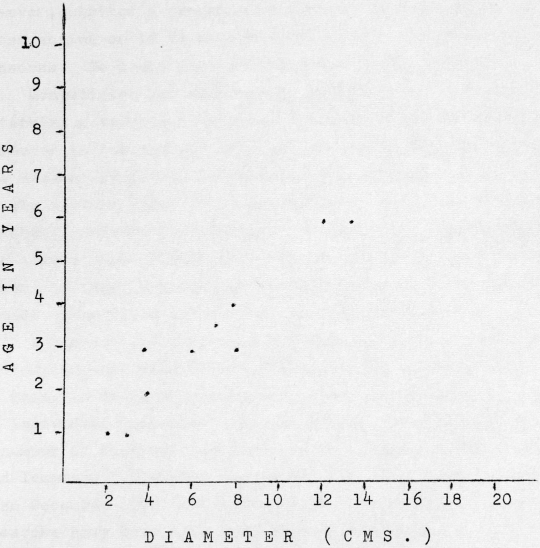

Figure 6. Size-diameter relationships of ten tussocks from Plot 4, Ogotoruk Creek Valley, Alaska.

measuring 35 cms. in height are fairly common in areas where only one or two tussocks per square meter occur, though these areas are not like the situation found in Plot 54.

As already indicated, the availability of water plays a part in determining tussock size and density. Since tussocks almost always occur in groups, competition for space also plays a part, as does the intensity of frost action on the site. It is not clear, however, whether a decrease in numbers of tussocks favors increased frost action or if increased frost action decreases the number of tussocks. No doubt the two are inextricably related.

Competition for minerals is probably also of importance in determining tussock abundance. Because there is a low nutrient turnover in the tussock type, it is likely that the tussocks exhaust the mineral supplies in the areas surrounding them. This is supported by the work of Tamm (1954) in Sweden in which he demonstrated that he could increase the amount of living Eriophorum vaginatum stems and leaves nine-fold by applying phosphate fertilizer. Tamm worked in bogs, however, so the situations are not strictly comparable, bogs being notoriously poor in minerals.

A tussock field conveys the impression of considerable age. Geologists with whom I have discussed the problem are accustomed to think in terms of hundreds or even thousands of years as the age of individual tussocks. This is almost certainly an exaggeration. A number of factors contribute to the demise of tussocks. Voles and lemmings frequently choose tussocks for sites of nest building (see December 1959 Botanical Report, Figure 9); many dead or dying tussocks have been seen with their centers almost completely hollowed out by these animals. A somewhat exposed tussock may also be eroded by the wind and eventually killed. Large animals, either intentionally or accidentally, uproot tussocks as they pass. Water erosion around the roots of the tussock may expose its roots to drying. Frost heaving may uproot tussocks. And finally, it is possible that tussocks are "starved out" by extreme mineral depletion of the soil; senescent or dead tussocks have been seen in many parts of the Ogotoruk Valley where no other explanation seemed to suffice for their condition.

Unfortunately, practically nothing is known of the life history and ecology of Eriophorum vaginatum. The conditions under which tussocks become established, grow, and maintain themselves have been adumbrated in studies of arctic vegetation, but this information must be made available for any satisfactory solution of the frost scar problem in this vegetation type. For a description of tussocks in another part of Alaska, the reader is referred to Hopkins and Sigafoos (1951: 70-76).

We are primarily concerned here with the effects of frost action on tussocks, especially the influence of frost scar formation. When a frost scar forms in Eriophorum tussock vegetation, as elsewhere, the soil is elevated above the surrounding surface. This microtopographic discontinuity is too much for the tussocks subjected to this disturbance, and they perish for one of several reasons. In the most extreme cases, they are overturned and die at once, or later if some of their roots maintain a tenuous contact with the soil (Figure 7). In those instances where the tussock remains upright on the convex surface, it is exposed to the severe dessicating and eroding effects of the wind and is gradually killed over a period of years (Figure 8). Also, because of its elevated position, rains accompanied by winds wash soil away from its roots. In any event, thriving tussocks are almost never found on convex scar surfaces. Thus, as in the wet meadow type, active frost scars are characterized by denuded surfaces.

The later events that occur in the maintenance of frost scars in the Eriophorum tussock type are related to the habitat characteristics of the type. If should be recalled that tussocks grow on drier soils than those of the Eriophorum-Carex wet meadow, and in the valley proper occur generally at slightly higher elevations. Because of the ubiquitous character of permafrost, the word "dry" is a relative term in discussing the moisture relationships of the vegetation types here. Under the Eriophorum tussock type, however, permafrost is deeper by some 10 to 15 cms. than in the Eriophorum-Carex wet meadows. The deeper permafrost and the greater exposure means that frost scar surfaces are more likely to be susceptible to erosion than those of the wet meadow type.

Figure 7. A partially overturned tussock near Plot 34. Dead portions of the tussock can be seen; also note erosion of tussock base. Ogotoruk Valley, 28 June 1960.

Figure 8. A tussock on frost scar surface undergoing wind erosion. Large leaf at base of tussock is Petasites frigidus, a common frost scar invader. Ogotoruk Valley near Plot 54, 9 July 1960.

Figure 7 (above) Figure 8 (below)

Once a frost scar has formed in the Eriophorum tussock type, it may remain active for an unknown period of time. Nothing is known of the complex of physical factors which maintain activity from year to year or of those which cause the scar to wane in its action. Eventually, at least in my opinion, scar surfaces become stable and later events may follow at least two separate paths:

1. Plants of drier habitats may colonize the scar. The first species successful in scar pioneering are most often grasses, especially Deschampsia caespitosa, Festuca brachyphylla, and Hierochloe alpina, and the sedge Carex bigelowii. As a matter of fact, though these species are found elsewhere in the valley, they are most common in these rigorous environments, and they are among the few species that seem to be able to reproduce by direct seeding onto the scar surfaces. A host of species may invade the scar laterally by sending out rhizomes and stolons over and through the scar surface from areas in which they grow adjacent to the scar; among them are Salix pulchra, Betula nana, Ledum decumbens, Salix phlebophylla, Vaccinium vitis-idaea, and Petasites frigidus. Not all of these species are present at once, as it is largely a matter of chance which of them happens to be in a favorable position for invasion. Also, the total moisture range over which the tussock type occurs is considerable, and moisture levels that do not exceed the amplitude of the tussock type may easily exceed that of some of the individual associated species. For example, of the species named as scar pioneers above, Salix pulchra is usually found ranging from the wettest to the driest tussock habitats, while Salix phelbophylla is associated only with those tussocks on the driest sites; so while the former is a potential scar invader in any tussock habitat, the latter is not seen on the scars in the wet portions of the habitats. This does not mean that Salix phlebophylla could not grow on the dry surface of a scar even in wet tussock habitats; rather it means that the species does not invade these habitats by seeding, but instead relies on vegetative propogation in these cases. Renewed activity of the scar surface may repulse the invasion temporarily, but eventually the plants may be successful and the domed mass of the scar supports a tough resistant sod composed of several of the above named species (Figure 9). In such situations the

Figure 9. Vegetation forming tight sod over surface of frost scar in tussock type. Species include Ledum decumbens, Carex bigelowii, Vaccinium vitis-idaea, Petasites frigidus, and others. Ogotoruk Valley near Plot 4, 13 July 1960.

convexity of the scar surface will probably be maintained even if the ice lenses beneath the scar surface melt out, because the roots of the plants will support the upper soil layers.

2. Probably much more commonly, scar surfaces are eroded away by wind and water and gradually reduced in height. On windy days in the summer and in the winter one can observe the powdery soil of dry scar surfaces blowing away. It has already been demonstrated that the scar surfaces in many sites are exposed in the winter (see June 1960 Botanical Report, p. 30). The Project Chariot geologists with whom the problem has been discussed suggested that some of the large amount of silt observed on the sea ice off Ogotoruk Creek perhaps owes its origin to frost scar erosion. There is other evidence to support this contention. Clumps of *Deschampsia caespitosa* are frequently observed to have been eroded away or killed by surface erosion of the scar (Figure 10). Also, roots of some of the scar invaders are often seen on the bare scar surface where they have been exposed by erosion (Figure 11). Finally, the scar is probably gradually lowered by compaction of the soil which had been loosened during heaving. Thus, under the combined influence of water and wind erosion, soil compaction, and possibly ice lens melting due to greater heat penetration on the bare surfaces, the scar surface sinks lower and lower until eventually it corresponds to the surrounding substrate. Concomitant with the depression of the scar surface is an increase in surface moisture, and eventually *Eriophorum vaginatum* again finds a suitable habitat for its growth (Figure 12). Surfaces which have reached this stage are probably rapidly colonized by tussocks, and in a few years no trace remains of the scar. At the wet end of the tussock habitat, surface lowering may proceed to the point where *Eriophorum angustifolium* invades for a time (Figure 13), but in such cases the surface is probably gradually built up by soil and peat accumulation until tussocks are once again successful.

Presumably these cyclic processes may be reactivated on the same site in the future, though at the moment this is entirely speculative. Detailed soil studies may give a clue to the reasonableness of this suggestion.

The complex processes contributing to the observations recorded above are not as clear cut as indicated. Frost scars are not always

Figure 10. A clump of Deschampsia caespitosa undergoing erosion and destruction on frost scar surface. Ogotoruk Valley, 13 July 1960.

Figure 11. Eroding frost scar showing exposed root of Betula nana crossing surface. Ogotoruk Valley, Plot 54, 9 July 1960.

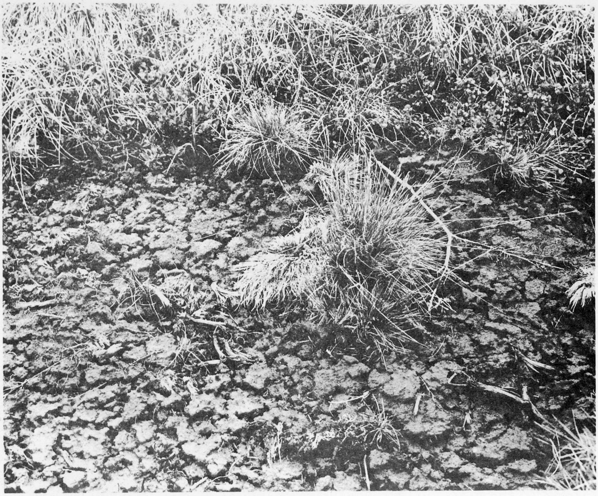

Figure 10 (above) Figure 11 (below)

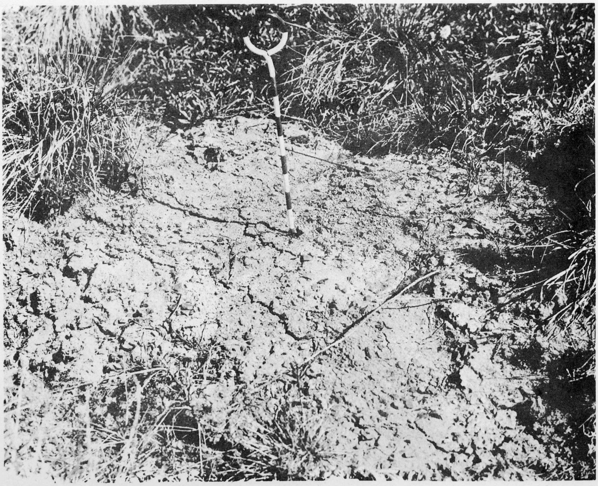

Figure 12. An old frost scar in the tussock type almost completely filled in by young tussocks. Ogotoruk Valley, near Plot 34, 30 June 1960.

Figure 13. Depressed center of tussock frost scar showing colonization by *Eriophorum angustifolium*. Ogotoruk Valley, 13 July 1960.

Figure 12 (above) Figure 13 (below)

either colonized or destroyed; the permutations of the two basic courses are almost as limitless as the variations in the sites on which tussocks occur. In this short discussion, I have tried to generalize on the subject and have lost much of what is natural under field conditions.

Carex bigelowii Frost Scar Type

There is an obvious transition from *Eriophorum* tussocks to the *Carex bigelowii* frost scar type, though the types do not always occur adjacent to each other. It has already been noted that the latter type is not present on the west side of the valley, and also it occurs in a few places where there are no tussocks in the immediate vicinity. The areas around Plots 13 and 35 are good examples of this situation.

For convenience, I shall refer to the *Carex bigelowii* frost scars as "pavement scars" in the following discussion. Pavement scars occur on coarse colluvial soils which contain sufficient quantitites of fine materials to render them frost susceptible. No data are yet available from the samples collected for soil analysis. For the most part the coarsest particles are from 3 to 5 cms. in diameter and are usually flattened and angular. The word pavement is appropriate to describe these scars because the tops of the best developed scars exhibit a hard, stony cover composed of these rock fragments. In somewhat less well-developed scars, the surface rocks are embedded in a hardened clayey matrix. Apparently some vertical sorting takes place in these scars, because the proportion of coarse materials becomes smaller with depth. Nevertheless, as there is no evidence of lateral movement of the coarse materials, these scars fall within the "unsorted" category. In the areas where pavement scars are best developed, they are larger than scars of either the tussock or wet meadow types (Figure 14). Plot 13 is a good example of this.

The soils of this type are better drained than those of the *Eriophorum* tussocks or *Eriophorum*-*Carex* wet meadows, partly because

Figure 14. A pavement scar in the *Carex bigelowii* frost scar type near Plot 54, Ogotoruk Valley, 20 June 1960.

Figure 15. A tussock-ring in transition area between *Eriophorum-Carex* wet meadow and *Eriophorum* tussocks near airstrip, Ogotoruk Valley, 13 July 1960.

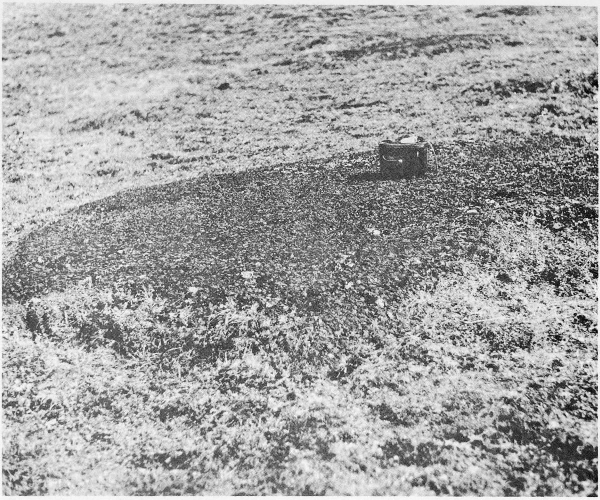

Figure 14 (above) Figure 15 (below)

of their coarser nature and partly because they are always found on somewhat steeper slopes than either of the other types. The improved drainage is mirrored in the deeper permafrost under the area. For example, on 20 June 1960, forzen soil averaged 29 cms. in depth under tussock scars in Plot 54, while just upslope from the plot in averaged more than 40 cms. in depth under pavement scars. Similarly, on 28 June, in the area near Plot 31, permafrost averaged 33 cms. in depth under the tussock scars, while under the pavement scars upslope from there, frozen ground was much deeper -- about 50 cms. In the short transition area between the two the depth averaged about 40 cms. Under the vegetation adjacent to the scars, the frost depth was about the same in all cases, averaging about 20 cms. Apparently the insulating properties of the different kinds of plants involved here are such that they compensate for textural differences in the soils.

In all cases where tussocks are found adjacent to pavement scars, a topographic break may be detected between the two types. Using the examples cited above, the slope increases by 2 per cent upslope from Plot 54, and in the pavement scar area near Plot 31, there was an increase from a 4 per cent slope in the tussocks to a 7 per cent slope in the pavement scar.

Because of their hard surfaces, pavement scars are exceedingly resistant to water and wind erosion, and their surfaces are inhospitable for most plants. As in the scars of other types, Festuca brachyphylla and Deschampsia caesptiosa are the most frequent plants found on pavement scars. Many of these scars are completely devoid of vegetation, however. Similar to the scars of the other types, invasion of the scar may take place from the side, and in these cases species of dry habitats such as the fell-fields are more important than uder the wetter situations of the tussocks and wet meadows. Salix phlebophylla, Dryas octopetala, Arenaria macrocarpa, and Betula nana may be mentioned in this respect. Again, the list is highly variable, but it is characterized by species more tolerant of dry conditions. Contributing to the inability of scars of all types to support plants is a tendency toward the production of drying cracks (miniature zellenboden of Troll, 1944) and of surficial frost crystals and even layers of ice in the winter (see June 1960 Botanical Report, pp. 30-31).

Once a pavement scar has been formed, there is much less tendency for it to be worn down by erosion or recolonized by plants than in the tussocks or wet meadows, and for this reason pavement scars probably last longer than the others. No clearly recognizable cycles were seen in the type, though more work needs to be done before any positive statement on the matter can be made.

As it is not the intention of this section of the botany report to give a complete description of the vegetation of the types, the reader is referred to the other section of the December 1960 Botanical Report.

Transitions

Special problems were encountered in the transitions between the Eriophorum-Carex wet meadow and the Eriophorum tussock types, and to a smaller extent between the Eriophorum tussock and Carex bigelowii frost scar types. In all of these cases the mechanisms responsible for the production and maintenance of the scars are probably about the same, but because the areas are transitional, the plants respond to small shifts in soil moisture and texture; therefore, the scars support unique mixtures of the plants of the overlapping vegetation types.

When a scar forms in the transition between Eriophorum tussocks and Eriophorum-Carex wet meadows, its raised center is too dry for the establishment of Eriophorum angustifolium, and often too active for the establishment of Eriophorum tussocks. Along the margins of the scar, however, young tussocks may become established and grow in a circle outlining the scar. This is the "tussock ring" (Figure 15) of Hopkins and Sigafoos (1951:84-87). As activity in the center of the scar decreases, the portion of the scar inside the ring may be colonized by another ring of tussocks, "double rings," and eventually it may be completely filled in "tussock groups." If, on the other hand, inactivity of the scar is accompanied by depression of the surface, E. angustifolium fills in the center. In some cases, chance determines which of the two species shall gain the upper hand. One species is unable to replace the other once the latter has become established.

The tussock rings and groups in the Ogotoruk Valley are never surrounded by a peaty ring as described by Hopkins and Sigafoos from the Seward Peninsula, but otherwise the development pattern they suggest applies to what has been seen near the Chariot camp. Some of the best examples of tussock rings and groups are located between Ogotoruk Creek and the east airstrip.

In time, it is believed that tussock rings and groups are replaced by E. angustifolium (and its associates), and that like the frost scar cycles described from the wet meadow and tussock sites, patterns of activity and decline may be recognized.

When a tussock ring or group becomes established, for a time its environment is drier than the wet meadow which invests it. But as the activity of the scar becomes negligible or ceases altogether, the earth surrounding the tussocks becomes lower and lower and finally is as wet as the wet meadow soils. Water may stand around the bases of the tussocks, and the small mounds of mineral soil and peat on which they have been standing are eroded away. Tussocks of this sort may be recognized by their great height and "mushroom" appearance. With their support literally washed out from under them, tussocks like this may fall on their sides and die. If they are not killed for purely physical reasons, they may die for physiological ones -- most likely because of the excessively high water table. Wet meadow vegetation may then replace the tussocks, and in time all vestiges of the former scar will have disappeared.

The length of time required for a cycle of this kind is, like cycles in the wet meadow and tussocks types, almost impossible to determine without long term studies. If an aging method for tussocks can be devised, the problem will be very much simplified.

The transitions between Eriophorum tussocks and Carex bigelowii frost scars are narrower for reasons mentioned above in the discussion of the latter. Little attention was devoted to these sites in 1960, and there is little to add to what has already been noted. These transitions are noted especially for the great decrease in numbers of tussocks with a coresponding increase in frost scars and in plants of drier habitats. No cyclic processes were noted.

Wet meadow vegetation is bordered on the still wetter end of the scale by ponds or lakes with their depauperate higher aquatic flora. Apparently, no underwater frost action occurs in the Ogotoruk Valley, though it has been demonstrated elsewhere. I have seen beautifully sorted polygons under the shallow alpine ponds or lakes in the Rockly Mountains of Colorado and similar phenomena are reported by Billings and Mooney (1959), though their interpretation of them are somwhat different than mine.

Summary

Eriophorum-Carex wet meadows, Eriophorum tussocks, and Carex bigelowii frost scar types are alike in that they each suffer periodic disturbances by frost action. They support strikingly different combinations of plants, and it may be suggested that they often show greater similarities in the plants that colonize their frost scars than they do in the plants of the mature expression of each type. The types themselves are seen to be differentiated primarily on the basis of soil moisture and soil texture characteristics, and clearly recognizable transitions occur between them. Cyclic patterns of frost scar formation, maintenance, and degradation occur in at least two of the types, the tussock and wet meadow, and perhaps as well in the Carex bigelowii frost scar type. Details of the cycles must still be worked out; another season of work on problems having to do with the vegetation will undoubtedly clear up many of these questions. Great gaps exist in the knowledge on the origin and other physical processes relating to the scars. Why frost scars occur in some places and not in others in a type is not understood; the variations in year to year production of scars is not known. During some years apparently many scars form; in others practically none. What are the factors leading to the stabilization and eventual inactivity of scars? How old are individual scars and how much time is required for complete frost scar cycles?

The literature, though voluminous on the descriptive aspects of rost action, is of little help in answering these questions. Long term investigation combining the experience and insight of geologists, soils scientists, climatologists, and plant ecologists are needed. It is suggested that the Ogotoruk Creek Valley is admirably suited for such studies.

Other Vegetation Types

Most of my time during the field season of 1960 was spent in the three types discussed above; therefore, little time was spent in the other vegetation types. On the basis of what was observed, however, a few remarks can be made.

Dryas Fellfield

Little current frost action was seen in any of the fellfield communities visited. A few small, sorted circles are found on the Crowbill Ridge in areas of limestone residual soils (see above, p. 20), and several fossil sorted polygons of large size were seen along the eastern edge of the top of Crowbill Ridge. Neither of these types was studied. Some ancient stone stripes and black fields are also seen on the sides of Crowbill, but they too are inactive. Almost no evidence of patterned ground was seen on the shale fellfields which are so common on all sides of the valley. The reasons for this are discussed above (see pages 7 - 9).

Dryas Steps and Stripes

Inasmuch as *Dryas* step and stripe types are believed to be closely related to each other, they will be discussed together. As noted in the December 1959 Botanical Report, the dividing line between the steps and stripes seems to be slopes of about 10°, stripes being mostly limited to slopes steeper than that and steps on more gentle slopes. This distinction must not be taken too literally. Even on the most gentle of the step areas, there is a tendency for the steps to be oriented diagonally upslope and this tendency becomes more marked as the slopes steepen.

An insufficient number of observations were made to generalize on the steps and stripes in the valley; for this reason, I shall describe the situation as it was found in only one area in the valley on the Crowbill Ridge almost directly north of the Chariot base camp. Here on slopes of about 10°, on deep calcareous soils, are well-developed steps, and on the somehwat steeper slopes above there, stripes are seen.

The flat portions of each step are covered with surficial layers of coarse gravel which average about 4 cms. in diameter. The width of the bare, gravelly portion of the step varies from about 10 cms. to 1 meter. The areas are not perfectly flat, but tend to slope slightly downhill (Figure 16). The front parts of the steps are faced with dense mats of Dryas octopetala and a rich flora of other plants interspersed in the Dryas mat. The front of each step is from 10 to 30 cms. in height and up to one meter in width. The Dryas mats are tough and prevent most of the downslope movement of the bare soil on the surface of the step. In a few places small breaks were seen in the mat where soil was "flowing" through. Ground squirrels often initiate these breaks by feeding on the roots of the plants of the mat; fresh digging was observed in a number of places, and squirrels sometimes were seen feeding in these places.

The soil is deep and well-drained; no permafrost was encountered to depths of 75 cms. on 4 July 1960. Samples were collected for mechanical analysis, but the results are not yet available. It appears, however, that the soils are coarser at the surface, finer for about 25 to 30 cms., and then increasingly coarser again, presumably until bedrock is reached. Thus, some frost heaving occurs, bringing the coarser materials to the surface, but apparently no lateral sorting occurs. Frost action is weak and probably limited to the spring and fall freezing-thawing periods.

Each step is probably a small turf-banked terrace, in which movement is so slow that plants have an opportunity to colonize and subsequently stabilize the advancing frontal margin. Plants are kept from colonizing the upper surface of the step by the

Figure 16. Dryas steps in area west of Chariot camp. Note gravelly upper portions of each step and Dryas-banked fronts. Small breaks can be seen in the Dryas mat in several places. Ogotoruk Valley, 4 July 1960.

seasonal frost action that takes place there.

Dryas stripes differ little in appearance from Dryas steps, except for the orientation of the pattern. The reason for the presence of the vegetation is not obvious, but it may result from slight surface depressions as suggested by Washburn (1956: 837) or, as seems more likely to me, a small degree of sorting occurs, and the plants occupy the areas where fine materials are concentrated. I would suggest that this is one of those instances where the borderline between sorted and unsorted structures is obscure and difficult to interpret. As noted in the December 1959 Botanical Report, there are fewer species present in the stripes than in the steps, probably because of better drainage and shallower soils. No other observations were made in the stripe areas.

Other Physical Features of Influence on the Vegetation -- Mudflows

The rapid, viscous flow of fine-grained, saturated soil is commonly referred to as a mudflow. Mudflows are distinguished from other solifluction phenomena by the rapidity and the violence with which they occur. They are known from a great part of the world, but they are sufficiently uncommon and spectacular to provoke comment when they are seen. Tundra mudflows have been reported from many arctic areas. Sigafoos and Hopkins (1952) comment on their presence on the Seward Peninsula of Alaska, describe some typical forms, and cite other examples from the literature. They refer to them as "characteristic features of certain undisturbed tundra areas."

We have seen no mudflows in the Ogotoruk Valley proper, but have encountered some rather interesting flows just across the low divide separating upper Ogotoruk Creek from the watershed of the Kukpuk River at approximately 68°10' N. Lat.; 168°29½' W. Long. The geologists have commented on the presence of others in that general area. Mudflows must be considered rare features of the landscape in the study area.

The particular mudflow discussed below was found toward the end of the 1959 field season by the botanical party, but they did not have time to study it at that late date.

The general form of the mudflow fits the description provided by Sigafoos and Hokins (op. cit., p. 188) for the Seward Peninsula flows. The scar itself occurs in a semiciurcular niche, averaging about one meter deep and extending downslope about 50 meters and across the slope for about 30 meters. The wall from which the flow was detached is approximately at right angles to the slope, and a sea of bluish-gray, higly viscous, silty-clay mud lies in the area directly beneath the scarp and extending downslope for about 10 meters. Much of this is bare, and one soon becomes mired in it if attempting to walk across it. Floating on this sticky substrate are individual tussocks and clumps of other vegetation which quite obviously did not grow there, but which were carried into the area when they became detached from the vegetation above the cut.

There are several unusual features about this mudflow which are worthy of comment. First, the flow occurs on a gentle slope of only 2°, which is much shallower than flows reported from other areas. Secondly, close examination reveals that this particular flow did not spew down the slope in one great mass, but rather it is being increased in size annually by augmentations from the face of the cut. There are several reasons for making the second statement: the area immediately below the cut is much "fresher" than the part of the flow downslope from it; it supports only pieces of vegetation that have fallen into it, while the lower end of the flow is completely covered with a mixed tussock-wet meadow vegetation, and thus is believed to be considerably older. Part of the suface of the flow below the fresh area is thrown up in folds 40 to 60 cms. high (Figure 17) which gives one reason to suppose that it was "pushed" from above by later flows. Furthermore, as will be seen below, examination of some of the details of the surface pattern immediately above the cut provide clues to explain the idea of regular augmentation.

Excavations made both above and below the cut show that permafrost is present at depths of 30 to 50 cms., and though it

Figure 17. Folded tundra surface below mud scar area. Folds were produced by pushing from the mud scar area located to the left of picture. Divide between Ogotoruk and Kukpuk drainages, 13 July 1960.

is highly variable, its general surface is parallel to the slope. On digging out the base of the cut, however, a significant observation was made. Permafrost at that site was found at about 50 cms., but it occurred as a clear layer of ice oriented at an angle of about 37° from vertical. Therefore, though the angle of the slope is only 2°, the soil is actually slipping forward on an icy plane which is nearly 20 times that steep. Behind the face of the cut, the angle of the permafrost gradually decreases until at a point upslope far enough to preclude the influence of the insolation on the cut face, the level once again becomes parallel with the slope angle. This is shown diagrammatically in Figure 18.

Another observation of general importance was made in the area. The vegetation over the area surrounding the mudflow is tussocks. Frost scars are exceedingly abundant here and are of the sinuous type. In fact, they are many meters in length, and are separated from each other laterally by rows of tussocks; this gives the area a peculiar striped aspect (Figure 19). The alternate stripes of frost scars and tussocks are oriented at right angles to the slope, this general pattern extending up to the edges of the mudflow both above and below it. It was enlightening to nate that above the cut face, the striping pattern was parallel to the edge. This last observation seemed to tie up the loose ends of the puzzle, and lends credence to the suggestion that small mudflows of more or less regular occurrence are responsible in aggregate for the great mass of mud below the cut face. The sequence of events giving rise to a single mudflow might then be explained as follows and in Figure 18:

During the summer season, the insolation of the steep, dark cut face causes a rapid retreat of seasonal frost and a steepening of the permafrost beneath it. In late summer, heavy rains often fall in the area and the ground becomes saturated. Water percolated down only to the surface of the permafrost and then runs down its steep face. The frost scar lying above the cut is a zone of weakness in the soil; few plants grow on the scars. When maximum saturation of the soil occurs, one complete

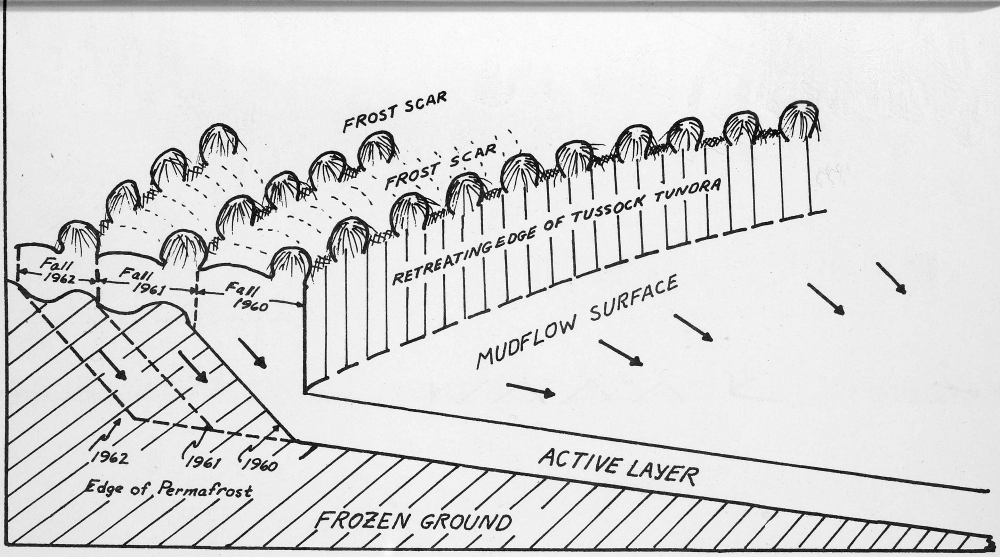

Figure 18. Diagrammatic cross-section of mudflow area. Angle of slope both above and below retreating vertical edge of tussock tundra is 2 degrees. Permafrost parallels surface, except behind vertical bank where it tends upslope at about 37 degrees. Earth slides forward on this steep surface in yearly increments under influence of seasonal melting and heavy rains, probably in the fall of each year.

Figure 19. Frost scars of sinuous type separated by rows of tussocks. Note face of mudflow in left background. Kukpuk Valley in center background. 13 July 1960.

Figure 20. Tundra surface above vertical bank of mudflow. Vegetation on right is tipping to right while definite line of settling can be seen extending diagonally from lower left to upper center. Break occurs along frost scar. Mudflow area, 13 July 1960.

Figure 19 (above)

Figure 20 (below)

section of earth may suddenly collapse for many feet along the face of the cut. This section includes a row of tussocks growing on the very edge of the cut and the frost scar adjacent to it. The next line of tussocks may be as far as one meter upslope from the edge of the cut, and under it permafrost is higher; the tussocks themselves and the permafrost offer resistance to further sliding. The same sequence of events may be repeated during the next year, and in fact would not occur only if the late summer and early fall pre-freeze-up periods were dry. On walking along the entire edge of the cut, one area, which had already started to slide a little, was noted, and it confirmed the general scheme outlined above (see Figure 20).

Surely not all arctic mudflows occur in this manner. Nor do these suggestions explain what initiated the first flow of the series. There is a small drainage present in the area below the flow, and it is possible that one or two years of rapid erosion and cutting by this stream exposed the first cut bank which made all of the later events possible. The area is almost perfectly suited for a study of earth flow under natural conditions, and it is hoped that the soils scientists or the geologists will investigate the area in considerably greater detail.

SUCCESSION AND CLIMAX IN THE OGOTORUK VALLEY, A PRELIMINARY DISCUSSION

A great deal has been written in recent years about the problems of plant succession and the climax in the arctic, and it is inevitable in any study dealing with the arctic vegetation that some comment be included on these matters. I shall not review the pertinent literature extensively here, but such a review has recently been contributed by Churchill and Hanson (1958).

It must be remembered that the concepts of succession and climax in the vegetation were first elucidated in the temperate parts of North America -- in areas characterized by considerable uniformity and stability in soils and vegetation, and where successional processes seemed to be progressive, i.e., leading to greater order and complexity from disorder and simplicity. Because of these features, Clements and his followers evolved the monoclimax hypothesis in which the ecologist trys to imagine what the vegetation would look like if left undisturbed over long periods of time under the influence of a constant climate. In such a scheme, only the climatic climax vegetation is permanent, and all other pieces of vegetation are considered successional, no matter how permanent they may seem to be in terms of time intervals less than geologic.

Many recent workers take a more realistic attitude toward the recognition of vegetation units and consider that any unit in apparent equilibrium with some factor other than climate, e.g. soils, should be given climax status; this kind of philosophy is known as the polyclimax approach, and it is more popular with American ecologists today.

As research in the American vegetation moved into the north, it soon became apparent that successional processes in the arctic are different, in some ways, than those of temperate North America. In particular, some vegetation units may be replaced by different plants through a great variety of physical and biological processes, and some of these changes may be clearly seen to be downgrade or retrogressive changes, which is in opposition to the general Clementsian notion that backward development is impossible. Retrogressive changes are usually characterized by "decreases in one or more attributes of a succession, i.e., of complexity, diversity, stability, productivity, self-maintenance, uniformity within and between stands, and soil maturity" (Churchill and Hanson, 1958:155).

The reasons for retrogressive changes in the arctic vegetation are generally held to be due to the exigencies of the northern environment which creates disorder, especially in the substratum. The combined influence of wind, water, and temperatures prevent the development of mature soils which are in turn responsible for the progressive development of the vegetation.

The problem is further complicated in the arctic by the presence of few species, many of which have rather broad tolerances, so that "the vegetational contrasts are due to differences in dominance of some species, while a comparable shift in presence of species is less evident" (Dahl, 1957). Griggs (1934) called the arctic vegetation "weedy," which as I understand it has the same meaning as Dahl's statement. On the other hand, some of the arctic plant communities are characterized by great stability and exceedingly slow development, and though from a Clementsian point of view they would not be considered to be in equilibrium with the climate, to consider them as seral communities would be unreasonable. Selander (1950), for example, considers that "the climax communities of the Fennoscandian Mountains have remained essentially unchanged for the past 2,600 years."

All of our work in the Ogotoruk Valley points to the generalization that the vegetation is a mosaic which is distributed along numerous environmental gradients. Parent materials, soil moisture and texture, snow cover, frost action, permafrost, wind, and many other environmental factors are highly variable from one part of the valley to another. Our studies have indicated how the plants respond to some of these gradients. An "average"environment in the Ogotoruk Valley is a meaningless concept, and the application of a monoclimax terminology is not feasible. There are few indications of progressive changes in the area and probably all of the vegetation types we have described should be considered climax in the broad sense, though the use of the term has little value. Because of frost action one can find intracommunity successional sequences, especially in those communities where soils are most susceptible to frost. Some of the sequences are definitely progressive, e.g., the colonization and stabilization of a frost scar; in others, retrogressive changes are obvious, as in the subsequent breakdown of the same scar. These are the phasic replacement cycles of Churchill and Hanson (op. cit., p. 137) and of Watt (1947), and they operate within the community pattern as a whole. Following this thought a little further, a tussock "climax" would then consist of the tussocks plus all of the cyclic stages associated with frost scars operating within the general tussock environment.

Directional changes, i.e., the long-term replacement of one community by another, have not been positively identified in the Ogotoruk Valley. An example of this kind of change would be the long-term stabilization and colonization of frost scars by plants other than those which were present before the disturbance. It is possible that this happens in the Ogotoruk Valley, but the stages which were recognized may instead be parts of a cycle of longer duration than usual. The relationship of vegetation types as outlined in Figure 1 is not meant to indicate directional succession, but rather the relationships of the vegetation types to various environmental gradients operating in the area.

Thus, if for historical reasons one wishes to apply climax terminology in the Ogotoruk Valley, he must be aware that his definition must be modified to meet the local situations.

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